A numerical study on atmospheric general circulations of synchronously rotating aqua-planets: Dependence on planetary rotation rate and Solar Constant

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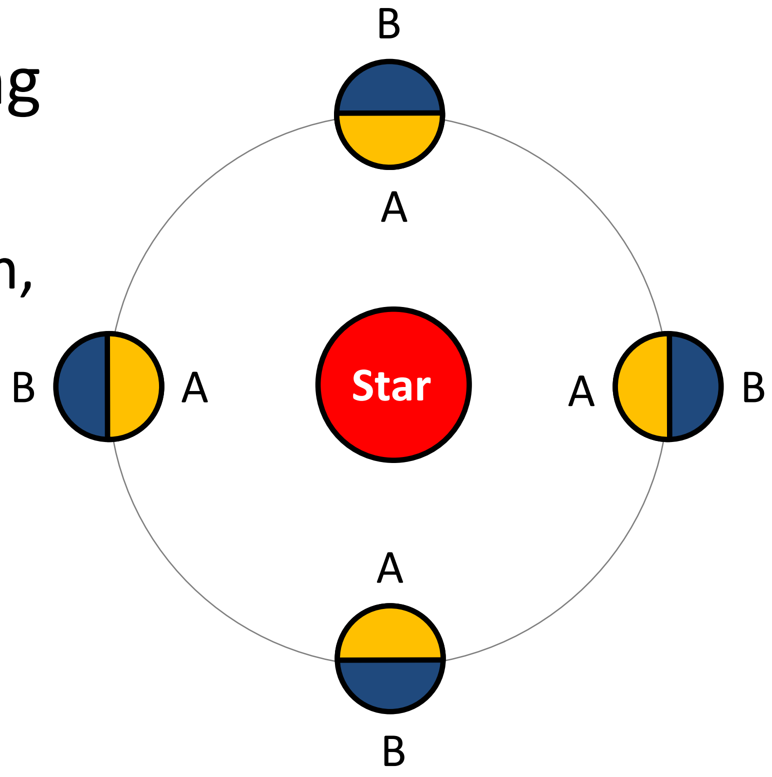
Synchronously rotating planets

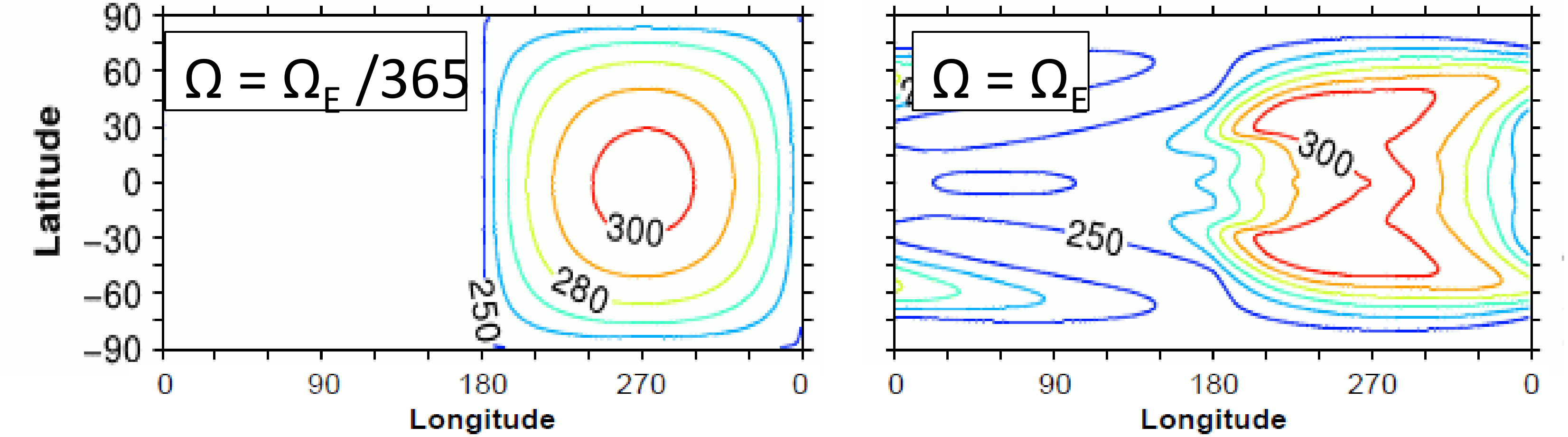
- Some terrestrial exoplanets are expected to be tidally locked and synchronously rotating.
  - fixed dayside and nightside
- Climates of synchronously rotating aqua-planets?
  - With solar constant of present Earth, day-side is in runaway greenhouse condition



Previous aqua-planet experiments

- GCM experiment with changing rotation rate.
  - – Joshi (2003): $\Omega/\Omega_E=1$
  - – Merlis and Schneider (2010): $\Omega/\Omega_E=1/365\sim1$
  - – Edson et al. (2011): $\Omega/\Omega_E=1/100\sim1$
- Equilibrium states are obtained in all cases.

Surface temperature(Merlis and Schneider, 2010)



Slowly rotating regime

Rapidly rotating regime

Aims of this study

- Parameter study with various planetary rotation rate (Ω) and solar constant (S)
  - Parameter dependences of circulation and energy transports ?
    - In previous works, cases with $\Omega \sim 0, \Omega_E$ are focused on.
  - Occurrence condition of the runaway greenhouse state?
    - The dependence on solar constant has not been examined in previous works.

Model

- Atmospheric General Circulation model：dcpam (http://www.gfd-dennou.org/library/dcpam/index.htm.en)
- Dynamical part：3-d primitive equation on sphere

Hydrostatic equation

$$\frac{\partial \Phi}{\partial \sigma} = -\frac{R^d T_v}{\sigma}$$

Equation of motion

$$\frac{du}{dt} - fv - \frac{uv}{a}\tan\varphi = -\frac{1}{a\cos\varphi}\frac{\partial \Phi}{\partial \lambda} - \frac{R^d T_v}{a\cos\varphi}\frac{\partial \pi}{\partial \lambda} + \mathcal{F}_\lambda,$$

$$\frac{dv}{dt} + fu + \frac{u^2}{a}\tan\varphi = -\frac{1}{a}\frac{\partial \Phi}{\partial \varphi} - \frac{R^d T_v}{a}\frac{\partial \pi}{\partial \varphi} + \mathcal{F}_\varphi.$$

Continuity equation

$$\frac{d\pi}{dt} + \nabla \cdot \boldsymbol{v}_H + \frac{\partial \dot{\sigma}}{\partial \sigma} = 0. \qquad \boldsymbol{v}_H \cdot \nabla_\sigma = \frac{u}{a\cos\varphi}\frac{\partial}{\partial \lambda} + \frac{v}{a}\frac{\partial}{\partial \varphi}$$

Equation of heat

$$\frac{dT}{dt} = \frac{R^d T_v}{C_p^d}\left\{\frac{\partial \pi}{\partial t} + \boldsymbol{v}_H \cdot \nabla_\sigma \pi + \frac{\dot{\sigma}}{\sigma}\right\} + \frac{Q^*}{C_p^d}.$$

Conservation of water vapor

$$\frac{dq}{dt} = S_q$$

Boundary Condition
$\Phi = 0$ at $\sigma = 1$
$\dot{\sigma} = 0$ at $\sigma = 0,1$

(λ, φ):longitude, latitude
$\pi = \ln p_s$
$\sigma = p / p_s$
$\dot{\sigma} = d\sigma/dt$
p: pressure
p_s: surface pressure
a: planetary radius
u: zonal wind
v: meridional wind
$\mathbf{v}_H$: horizontal velocity
T: temperature
T_v: virtual temperature
Φ: goepotential
f: Coliorils parameter
R^d: gas constant of dry air
C_p^d: specific heat of dry air
q: specific humidity
Q^*: external Heating
S_q: Source of water vapor
F_λ, F_φ: external forcin

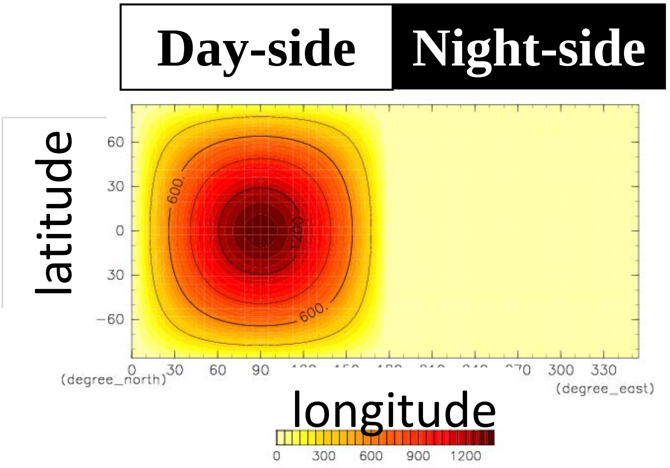
Physical Processes

Atmospheric composition	“Water vapor” and “dry gas”
Radiation process	Water vapor : gray to IR radiation Dry gas: transparent
Cumulus process	Convective adjustment (Manabe et al., 1965) condensed water is removed from system immediately (no cloud)
Turbulent vertical mixing	Mellor and Yamada (1972) Level 2
Surface condition	Aqua-planet, flat surface Zero heat capacity, no sea ice

Experimental setup

- Radius of planets, mean surface pressure, gravitational acceleration, and so on are Earth’s values
- Obliquity is 0

Incoming radiation flux



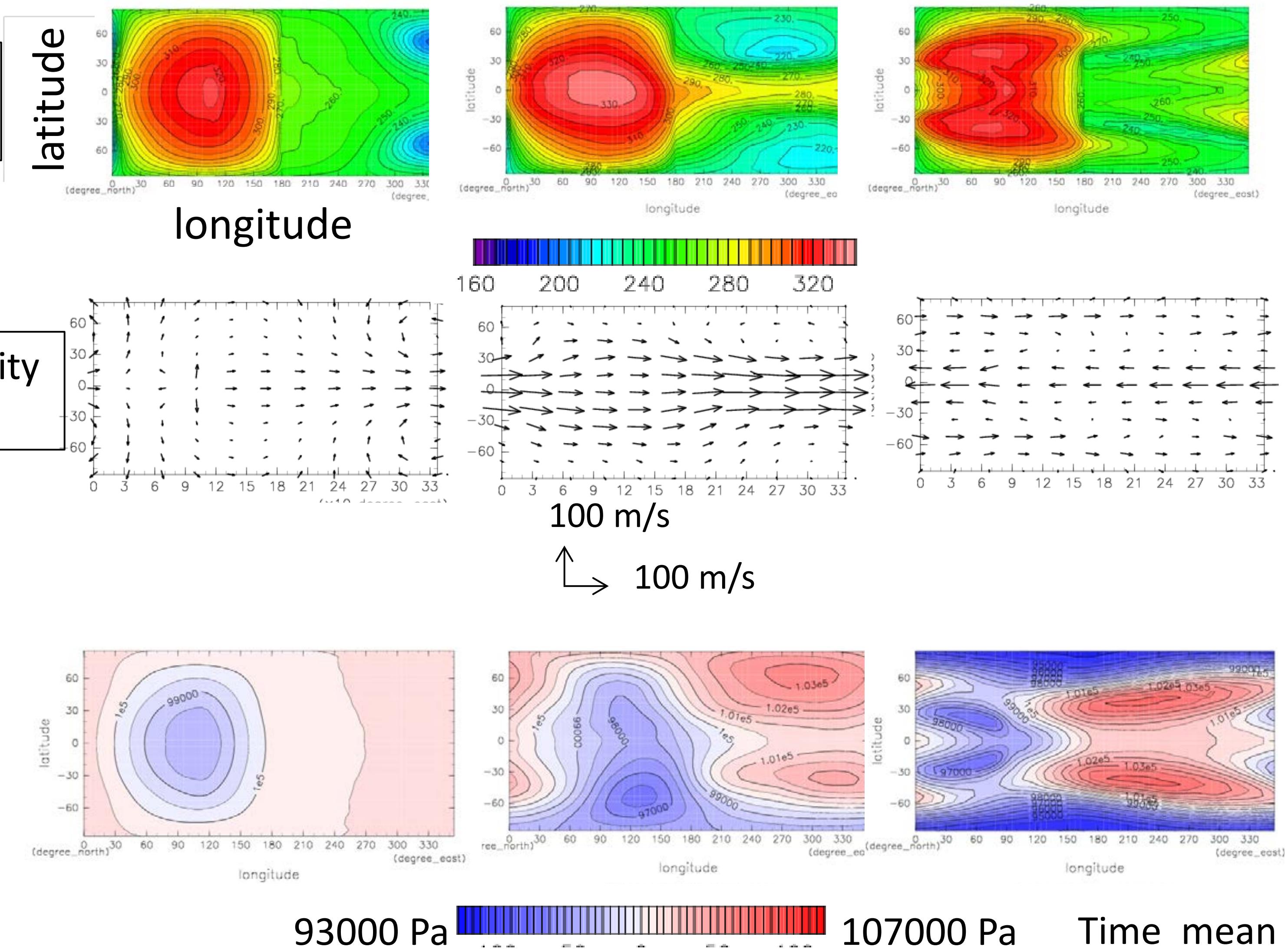
	Ω dependence exp.	S dependence exp.
Rotation rate Ω (Ω_E: Earth’s value)	0 - Ω_E (16 cases)	0, 0.15 Ω_E, 0.5 Ω_E, Ω_E
Solar constant S (global mean flux)	1380 W/m2 (345 W/2)	1380 - 1700 W/m2 (24 cases) (345 - 425 W/m2)
Resolution	T21L16 (64 x 32 x 16)	T21L32 (64 x 32 x 32)
Integration time	2000 day (last 1000 days are analyzed)	Over 2000 days (last 500 days are analyzed)
Time step	20 min	10 min or less

Dependence on rotation rate

- Experiment
  - Various Ω, fixed solar constant
- Results
  - In all cases, the runaway greenhouse states do not occur: statistically equilibrium state or oscillating state
  - Day-night energy transport is independent of Ω. Circulation pattern depends on Ω.

Atmospheric structure for various Ω

$\Omega = 0.05\,\Omega_E$ $\Omega = 0.67\,\Omega_E$ $\Omega = \Omega_E$



Surface Temperature

Horizontal velocity at sigma=0.2

100 m/s

100 m/s

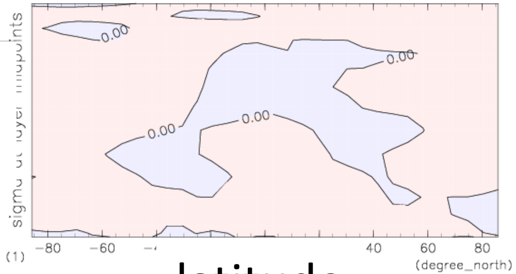
Surface pressure

93000 Pa 107000 Pa

Time mean over 1000-2000day

Zonal mean zonal wind for various Ω

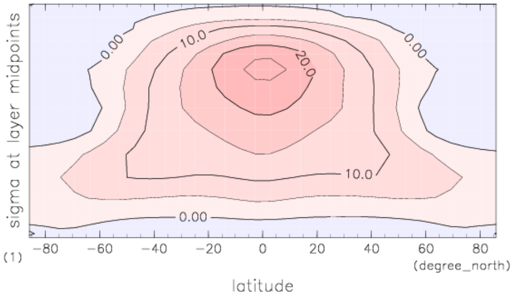
$\Omega = 0$



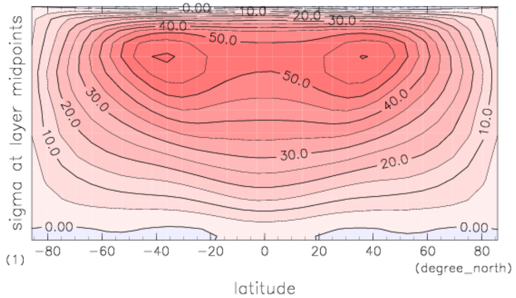
sigma

latitude

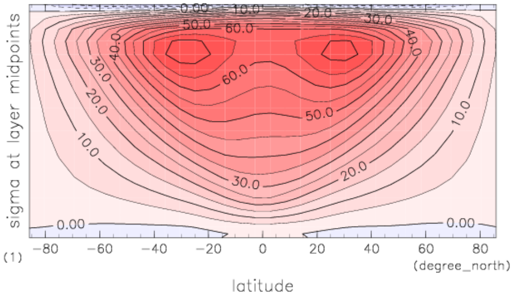
$\Omega = 0.05\,\Omega_E$



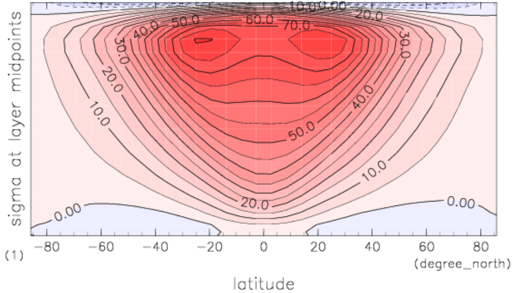
$\Omega = 0.15\,\Omega_E$



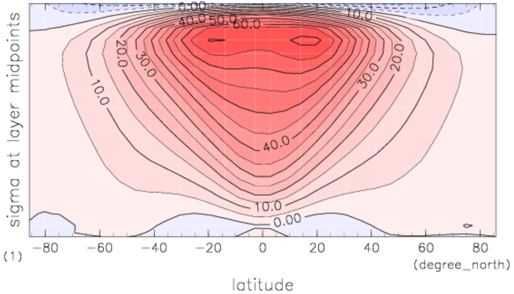
$\Omega = 0.25\,\Omega_E$



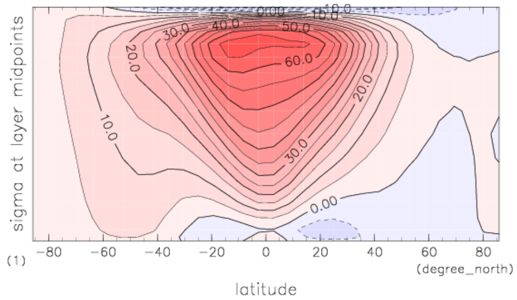
$\Omega = 0.33\,\Omega_E$



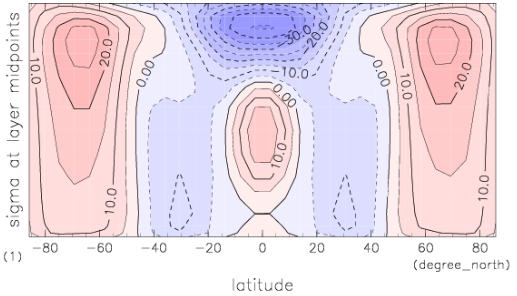
$\Omega = 0.5\,\Omega_E$



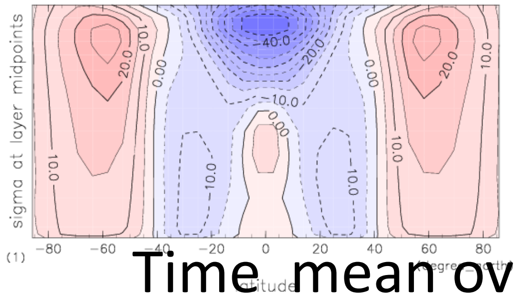
$\Omega = 0.67\,\Omega_E$



$\Omega = 0.8\,\Omega_E$

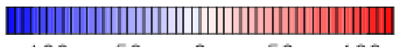


$\Omega = \Omega_E$



CONTOUR INTERVAL = 5.000E+00

-100 m/s



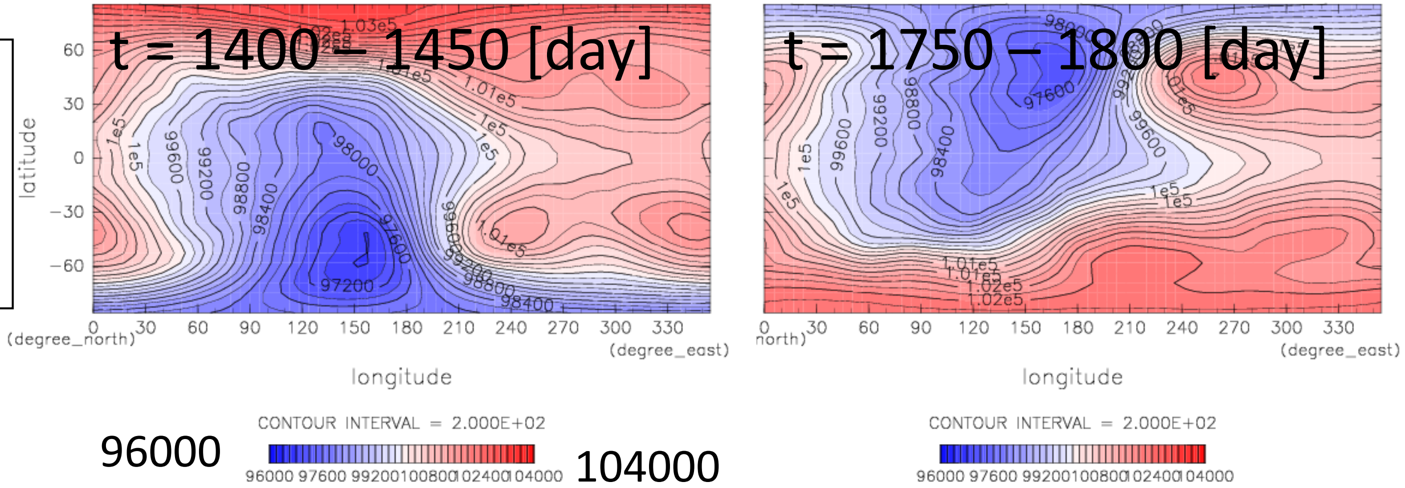
100 m/s

Time mean over
1000-2000day

Asymmetric state: $0.2\Omega_E - 0.67\Omega_E$

North-south
Asymmetric
State

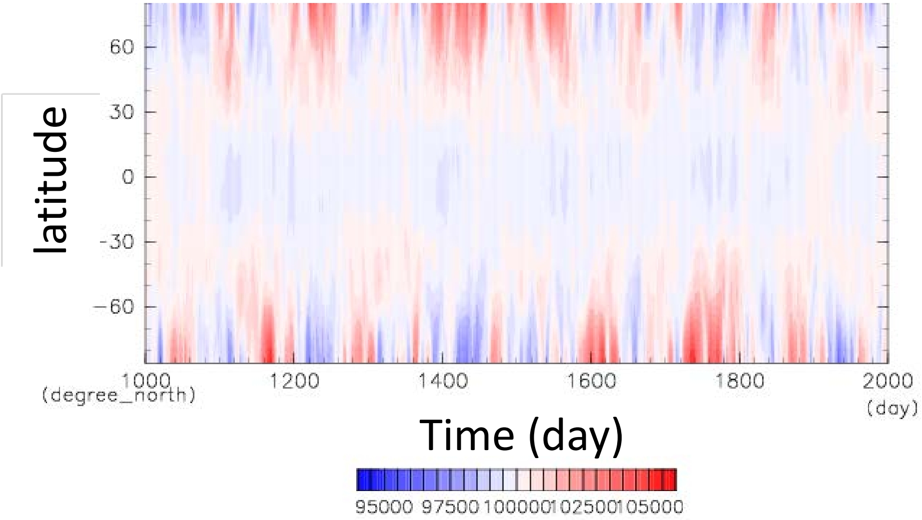
Surface pressure for $0.5\Omega_E$



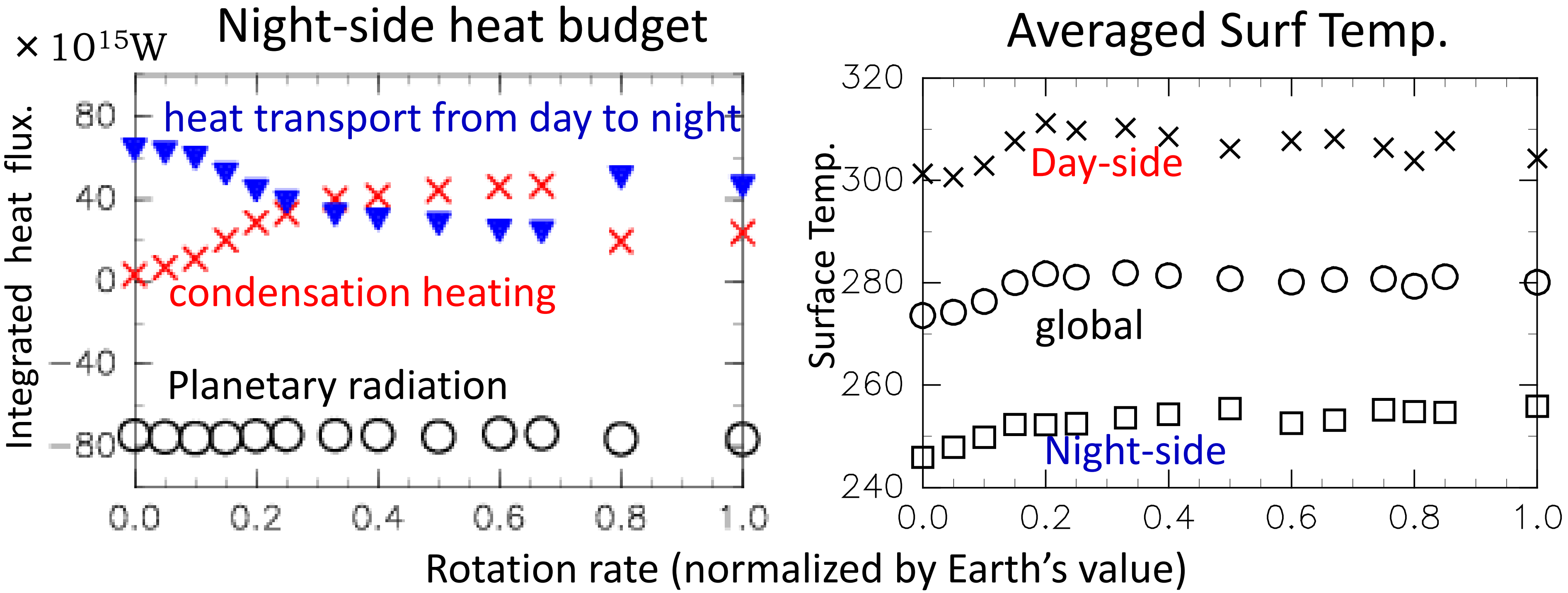
96000 104000

- Oscillation
  - Non-periodic for large Ω
  - “period”: 10day – 1000day
  - also in high reso. experiments

zonal mean surface pressure

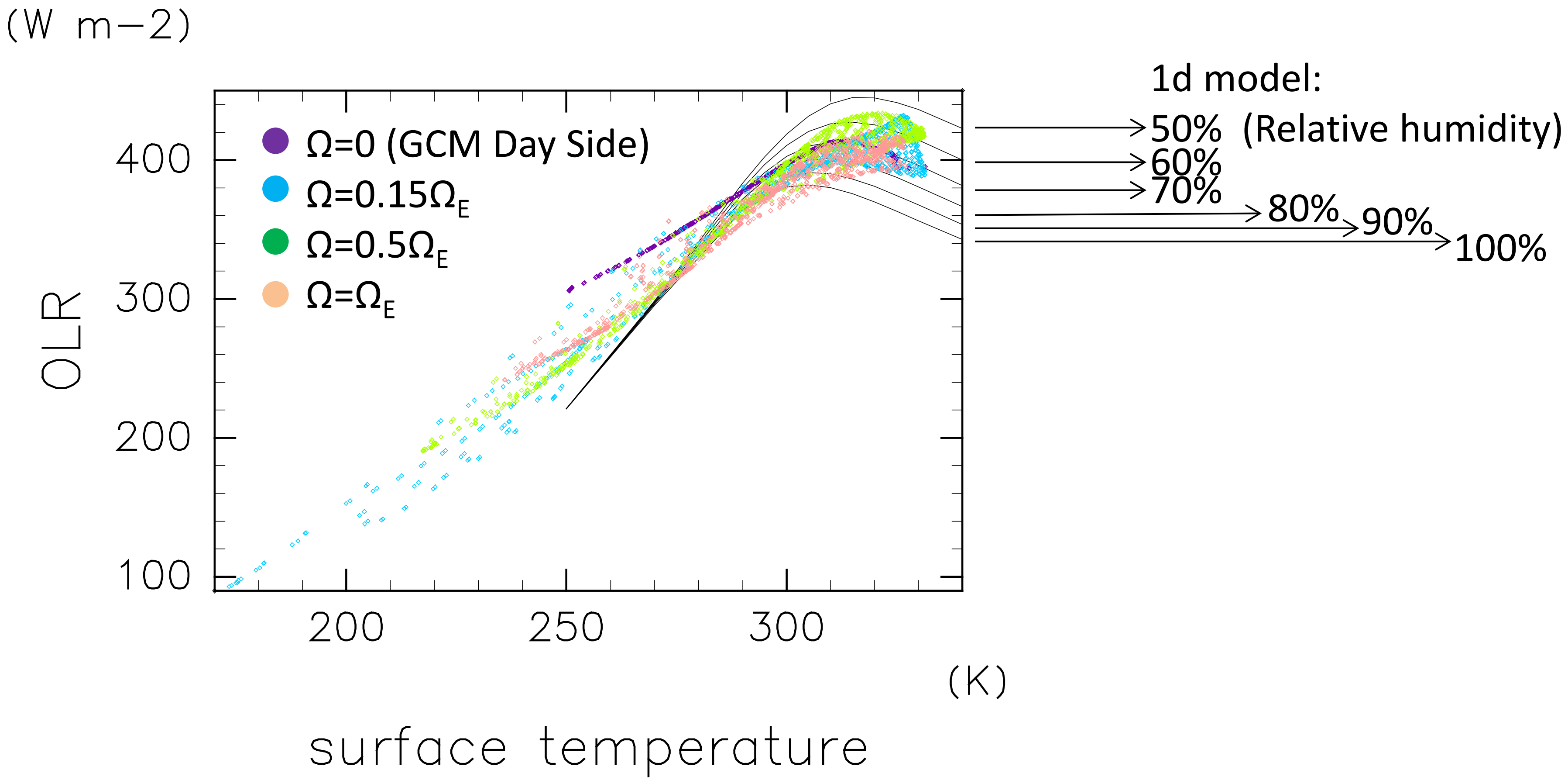


Dependence of heat budget on Ω



- Small dependence of summation of sensible/latent heat transports on Ω
- Total heat transport may be determined by (Incident solar flux) – (radiation limit)
  - Radiation limit: Nakajima et al. (1992), Ishiwatari et al. (2002)

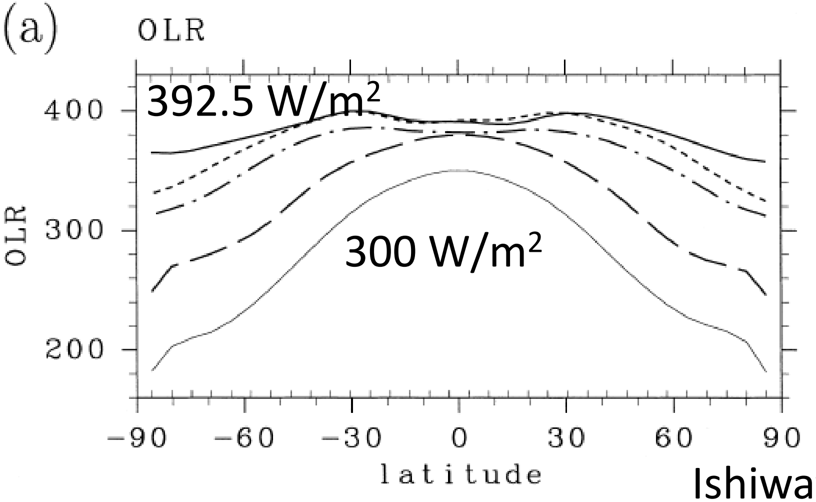
Comparison with 1-d model



- Outgoing Longwave Radiation does not exceed radiation limit obtained by 1-dim radiative convective equilibrium model.

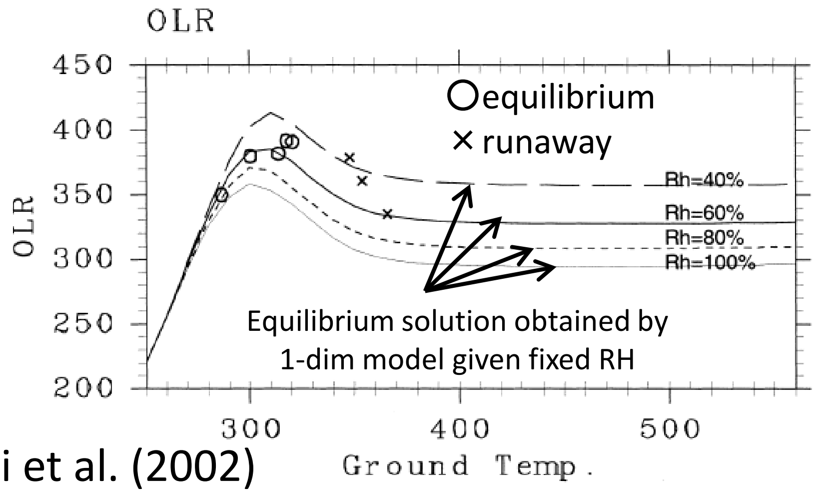
Dependence on solar constant

- Experiment
  - Various solar constant, Ω=0, 0.15 Ω_E, 0.5 Ω_E, Ω_E
- Aims
  - Does runaway condition corresponds to the radiation limit obtained by 1-dim model?
  - In non-synchronous rotating cases, runaway condition corresponds to the radiation limit.



392.5 W/m^2

300 W/m^2



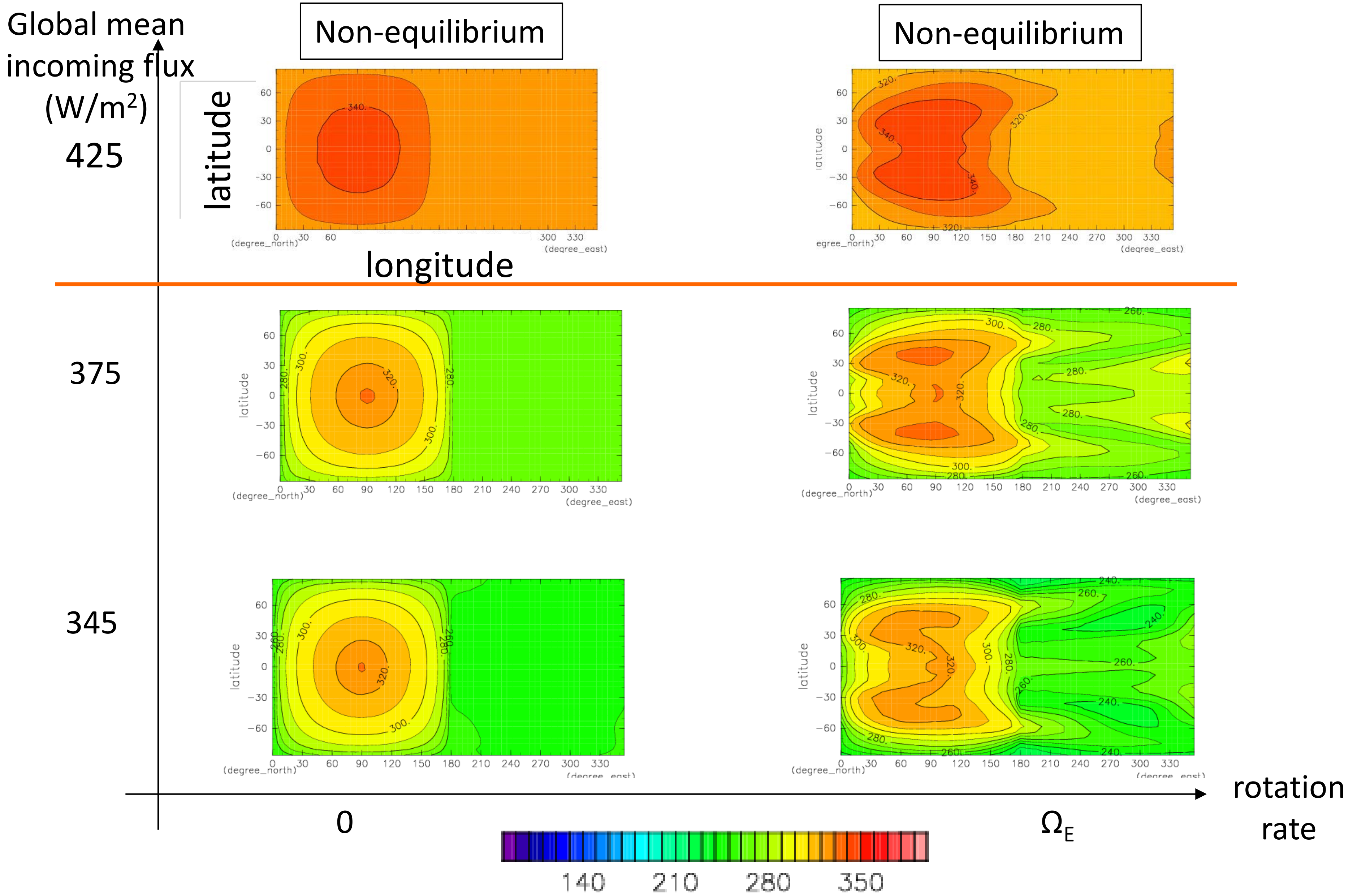
○ equilibrium

× runaway

Equilibrium solution obtained by 1-dim model given fixed RH

Ishiwatari et al. (2002)

Occurrence of Runaway greenhouse states



Global mean incoming flux (W/m^2)

Non-equilibrium

Non-equilibrium

425

latitude

longitude

375

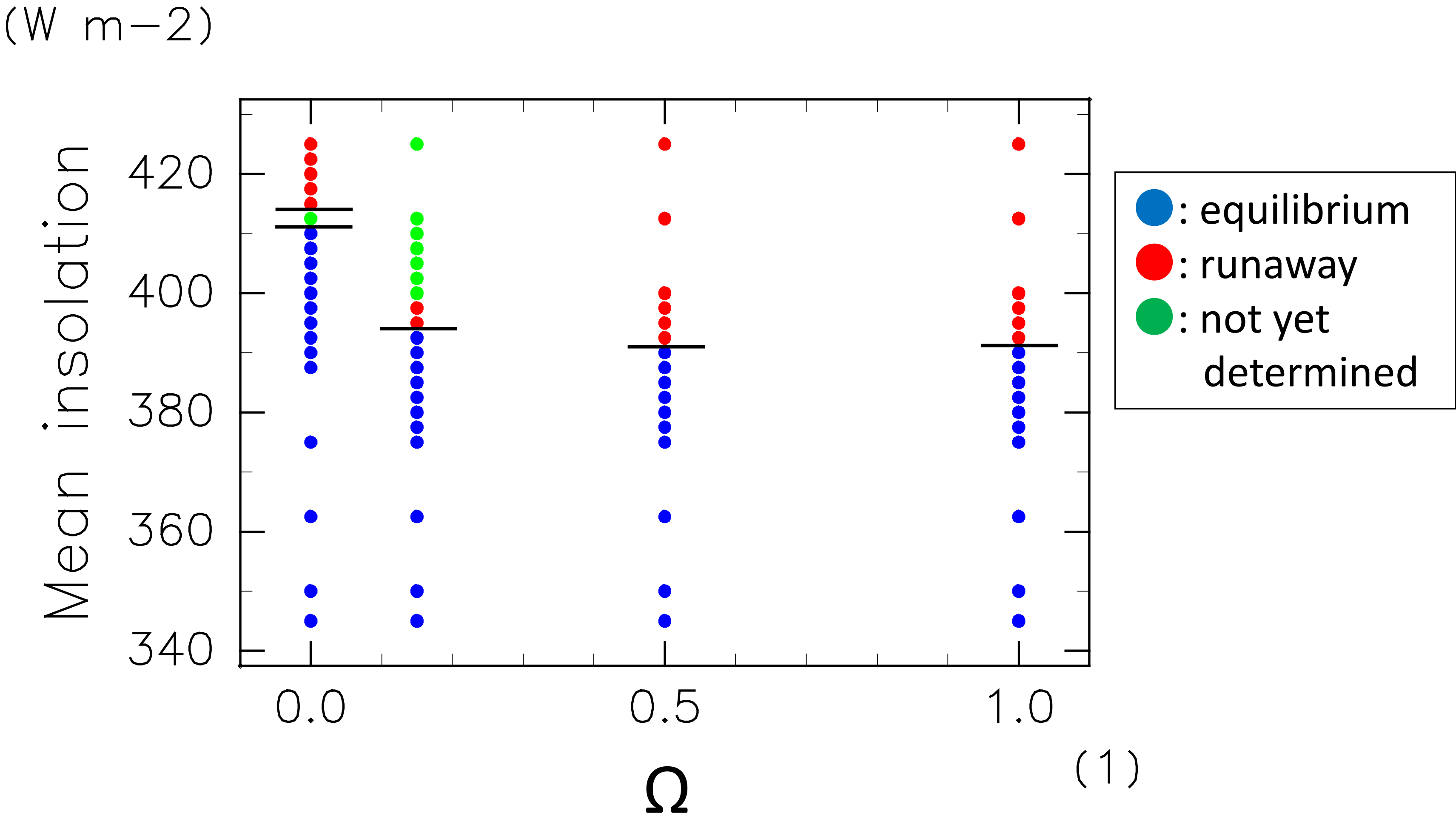
345

0

Ω_E

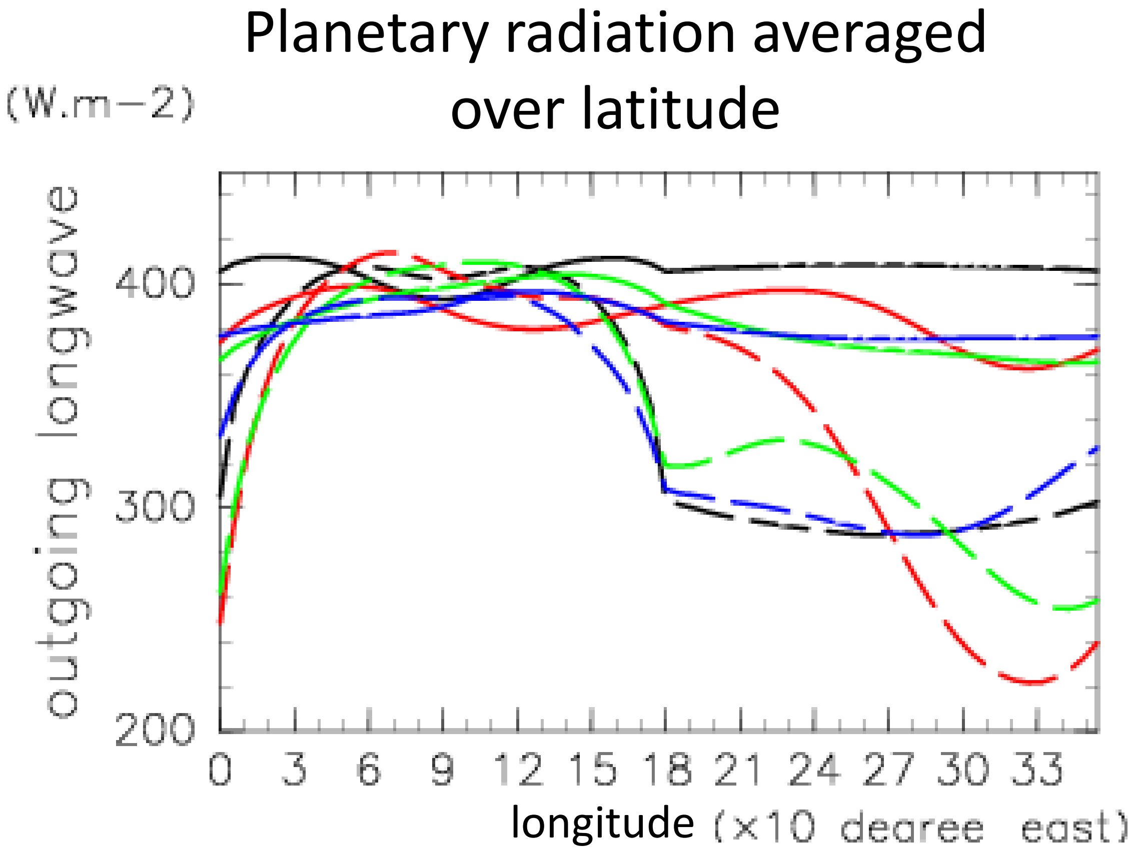
rotation rate

Results with various solar constant



The runaway greenhouse states occur when mean incident solar flux exceeds 400 W/m^2

OLR difference between day and night


Planetary radiation averaged over latitude

dashed line: present Earth S

solid line : just below runaway

$\Omega = 0$

$\Omega = 0.15\ \Omega_E$

$\Omega = 0.5\ \Omega_E$

$\Omega = \Omega_E$

- day-side OLR : almost constant against increasing S
- night-sde OLR : increase with increasing S

Summary

- Amount of day-night energy transport is independent of planetary rotation rate.
  - Day-side planetary radiation is constrained by radiation limit obtained by vertical 1-d radiative-convective model.
- It seems that occurrence condition of the runaway greenhouse state is described by the radiation limit.
  - Difference of planetary radiation between day-side and night-side decreases with increased solar constant.
- Circulation patterns does not depend on solar constant but on planetary rotation rate.
  - Day-night direct circulation, super rotation, oscillating asymmetric states